Renewable and Sustainable Energy Reviews 39 (2014) 342–355

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

The energy and water nexus in Chinese electricity production: A hybrid life cycle analysis

Kuishuang Feng [a,*], Klaus Hubacek [a], Yim Ling Siu [b], Xin Li [c]

[a] Department of Geographical Sciences, University of Maryland, College Park, MD 20742, USA
[b] Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK
[c] Oxford Institute for Energy Studies, Oxford OX2 6FA, UK

ARTICLE INFO

Article history:
Received 19 November 2013
Received in revised form
15 June 2014
Accepted 7 July 2014
Available online 31 July 2014

Keywords:
Electricity generation technologies
Hybrid life-cycle analysis
CO_2 emissions
Water scarcity
China

ABSTRACT

Between 2000 and 2010, China's electricity production had increased threefold and accounted for 50% of domestic and 12% of global CO_2 emissions in 2010. Substantial changes in the electricity fuel mix are urgently required to meet China's carbon intensity target of reducing CO_2 emissions by 40–45% by 2020. Moreover, electricity production is the second largest consumer of water in China, but water requirements vary significantly between different electricity generation technologies. By integrating process-based life-cycle analysis (LCA) and input–output analysis (IOA) and through tracking national supply chains, we have provided a detailed account of total life-cycle carbon emissions (g/kWh) and water consumption (l/kWh) for eight electricity generation technologies – (pulverized) coal, gas, oil, hydro, nuclear, wind, solar photovoltaic, and biomass. We have demonstrated that a shift to low carbon renewable electricity generation technologies, i.e. wind, could potentially save more than 79% of total life-cycle CO_2 emissions and more than 50% water consumption per kWh electricity generation compared to the current fuel mix and technology for electricity generation. If the projected wind farms are built by 2020, Inner Mongolia, one of the water scarce northern provinces, would annually save 179 MT CO_2 (i.e. 44% of Inner Mongolia's total CO_2 emissions in 2008) and 418 million m^3 (Mm^3) water (18% of its industrial water use in 2008) compared with the same amount of electricity produced from coal.

Contents

* Corresponding author. Tel.: +1 3014054567.
E-mail address: kfeng@umd.edu (K. Feng).

http://dx.doi.org/10.1016/j.rser.2014.07.080
1364-0321/

1. Introduction

China was a major player in the Copenhagen Accord [1] which was developed at the Copenhagen climate summit in December 2009. As a signatory of the Accord, China agreed to reduce its carbon dioxide (CO_2) emissions per unit of Gross Domestic Product (GDP) by 40–45% by 2020 from 2005 levels and increase the share of non-fossil fuels in primary energy consumption to around 15% [2]. The targets that China has set are of major consequence and, if met, will make a significant contribution to international CO_2 mitigation efforts and a shift toward sustainable, renewable energy sources at the national scale. A continuation of China's historic trend of declining carbon intensity since 1980 would seem to be sufficient to enable China to exceed its target range. However, this does not mean that achieving the target is easy, nor that the policies are sustainable. For example, the declining trend was reversed during 2003 and 2004, and further progress will not be sustained without strong Chinese government policy interventions. Even so, purely on the basis of meeting 15% of its primary energy requirements from non-fossil fuels, large investments in a transformed energy system with substantial changes in the fuel mix is a precondition for achieving this target. For example, according to a government report, China's spending to develop renewable energy may total US$294 billion (1.8 trillion yuan) in the five years through 2015 as part of the nation's efforts to counter climate change [3].

Several studies [4–7] can be found in the literature which examined the status, outlook and projection of China's energy sector. However, it is essential to examine the feasibility of the energy targets and more importantly, their implications and trade-offs (such as increasing water requirements). These trade-offs need to span the whole life-cycle of the respective technology as a new low-carbon energy system can reduce direct carbon emissions from the energy generation itself, but building a new energy system itself can be energy-intensive because upstream (i.e. indirect) emissions related to such capital investments can be significant [8]. Hence, there is a need for assessing life-cycle CO_2 emissions (both direct and indirect) of electricity production, particularly of the so-called low carbon energy generation technologies (e.g. nuclear, hydro, wind and solar photovoltaic (PV)) which can cause substantial CO_2 emissions in upstream production processes compared to fossil fuel based energy technologies. Total life-cycle CO_2 emissions refer to the direct and indirect CO_2 emissions per kWh over the lifetime of an energy generation technology; this includes CO_2 emissions during transportation of fuels, transmission of electricity, construction and operation of power plants, grid-connection and decommission of power plants. Direct CO_2 emissions are emissions released during the electricity production process while indirect CO_2 emissions result in upstream production processes (i.e. the previous production stages; e.g. CO_2 emissions released from manufacturing of electricity production technologies and associated inputs as well as their respective inputs).

The electricity sector is not only the major contributor to CO_2 emissions, but also one of the largest water consumers in China apart from agriculture [9]. Thus, the electricity sector can be a contributor to water scarcity which has already occurred in many parts of the country, in particular in Northern China [10]. As life-cycle water requirements for different types of electricity generation technology vary significantly, the choice of water-intensive power generation plants either exacerbates the problem of water supply in water scarce regions or constrains the efficiency of operating water-intensive power plants during water-shortage periods [11]. As argued by Cooper and Sehike [12], climate change mitigation efforts may have the risk of creating negative impacts on other aspects of environmental sustainability if such efforts become too focused on emission reduction. The energy water nexus has recently attracted lots of attention investigating the link of energy production and water consumption [13–16]. Hence, besides CO_2 emissions, there is also an urgent need for assessing direct and indirect water consumption from different electricity generation technologies.

Our research investigates whether low carbon electricity generation technologies really help mitigate CO_2 emissions and reduce water stress on existing water resources. In this study, we apply an integrated hybrid LCA approach to eight different electricity generation technologies in China to calculate their total life-cycle CO_2 emissions and water consumption throughout national supply chains. The selected electricity generation technologies are coal, gas, oil, hydro, nuclear, wind, solar PV and biomass that together contribute almost 100% of total electricity production in China. This is the first study to comprehensively examine the connection between embodied CO_2 emissions and water consumption for all major electricity generation technologies in China.

2. Electricity generation in China

China's electricity generation has substantially increased by 7.6 times over the last two decades (from 650 terawatt hours (TWh) in 1990 to 4940 TWh in 2012 [17]. Coal contributes approximately 80% to China's electricity generation followed by hydropower, accounting for 17% of the total electricity production. Increased concerns over climate change, national energy security and energy-related environmental repercussions in recent years have prompted the Chinese government to consider the transition to a low carbon electricity system [18–21]. Subsequently, a number of high level energy plans based on substantial increases in the shares of nuclear power, wind power and other low carbon emission power generation technologies have been introduced and implemented by the Chinese government (e.g. the Mid-Long Term Nuclear Development Plan [22] and the Mid-Long Term Renewable Energy Development Plan [23]). Two aspects are frequently addressed in the Chinese energy policies, namely, energy efficiency improvement and energy structure diversification. For instance, the Eleventh Five Year Plan (between 2006 and 2010) stated an energy efficiency improvement target of 20% by 2010 compared to the 2005 baseline [24]. In 2006, the first Renewable Energy Law was promulgated to legitimate and stimulate the development of renewable energy technology. The national strategy to climate change mitigation and adaptation was published in 2008 by the Central Government. The strategy developed the targets and plans in order to combat climate change and at the same time to diversify the energy structure and improve energy efficiency [25]. In 2009, the target of reducing the CO_2 emissions by 40–45% per unit of Gross Domestic Product (GDP) in 2020 compared with the 2005 baseline was delivered by

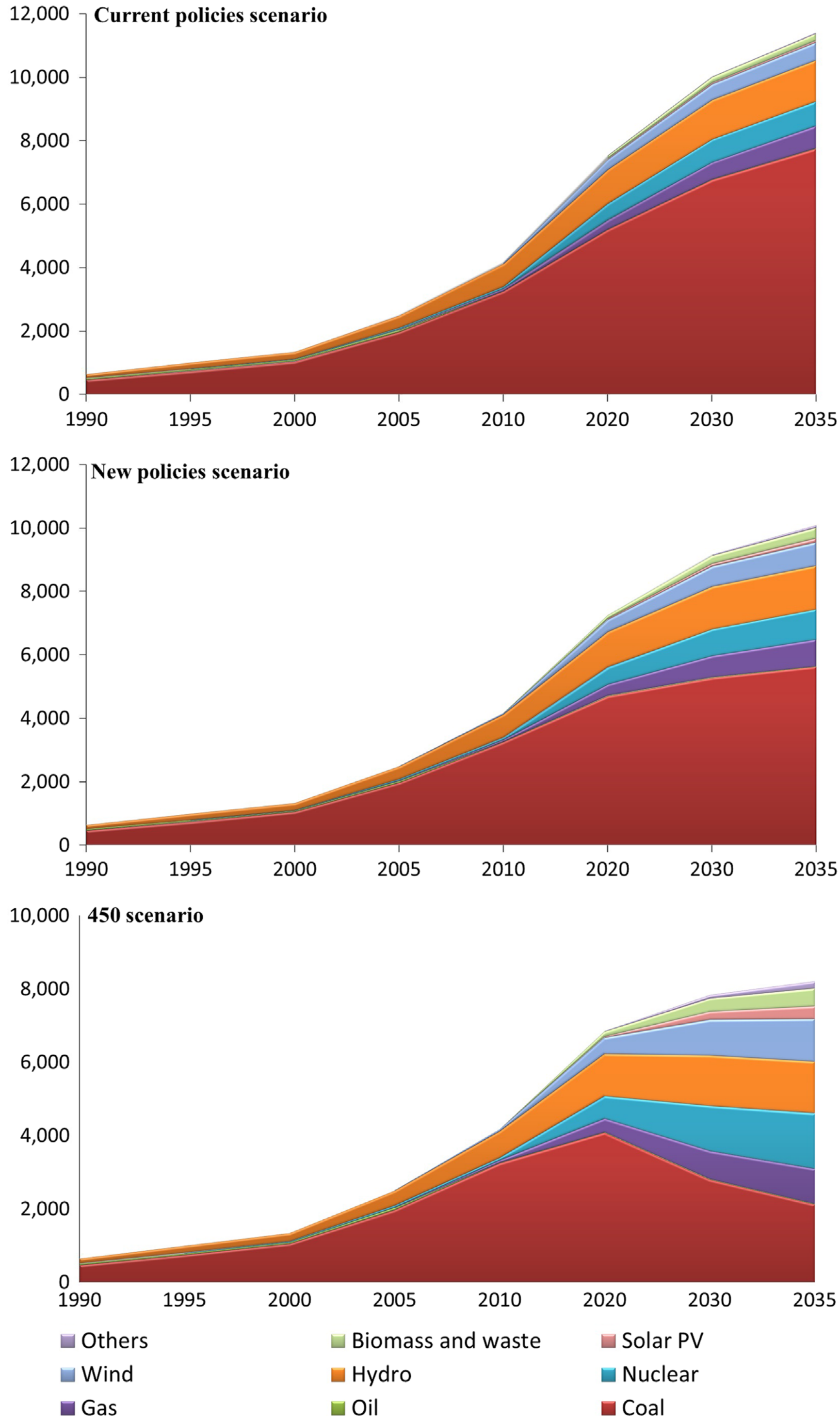

Fig. 1. The historical and future trends of China's primary electricity generation by source from 1990 to 2035, based on the International Energy Agency (IEA) scenario projections (TWh).
Source: Data for the historical primary electricity production (1990–2010) are collected from the IEA Statistics & Balances and the future projections (for 2020, 2030 and 2035) are based on IEA World Energy Outlook 2011 [30].

President Hu Jintao [26]. In addition, energy efficiency standards on lighting, building construction and house appliances either have been introduced or are being drafted by the Chinese government [27]. The 12th Five Year Plan on Energy Development (between 2011 and 2015) proposed dual targets on energy intensity reduction (16% compared to the 2010 baseline) and total energy consumption by 2015 (capped at 4 billion tons of coal equivalent compared to 3.25 billion tons in 2010) [28]. Although the shares of nuclear power and wind power in China's total electricity production are still insignificant, these energy generation technologies have enjoyed substantial growth over the last few years. For example, wind power generation has increased more than 17-fold from 2.8 TWh in 2006 to 49.4 TWh in 2010. Development of nuclear energy showed a similar trend. According to the World Nuclear Association [29], China has 15 nuclear power reactors in operation, 26 new nuclear reactors (out of a total of 60 reactors worldwide) are currently being constructed in China and most reactors have had their generating capacity of more than

1 Gigawatt (GW). Fig. 1 depicts past and future trends of China's primary electricity production by source from 1990 to 2035, based on information provided by the International Energy Agency (IEA).

According to the IEA's "current policies scenario", China's electricity generation from coal is projected to continue its rapid growth by 2035, and there is also an increasing trend of electricity generated from coal by 2035 based on the "new policies scenario" but with much lower growth rates [30]. In the IEA's "450 scenario", coal-based electricity production is expected to decline by 2020 due to a slowdown of electricity consumption (e.g. improvement of energy efficiency and slowdown of population growth) and heavy promotion of renewable energy to limit the long-term increase in the global mean temperature to two degrees Celsius (2°C) above pre-industrial levels has been criticized as an already elusive target. In addition to that, approximately 900 MW of coal-fired power generation units were installed in China every week in 2010 [31]. Considering the average lifespan of Chinese coal-fired power plants of around 40 years, the targets of IEA's "450 scenario" will not be attainable without aggressive government policies on carbon emission restrictions and extensive investments in alternative energy technologies. Also, thermal power generation technologies, such as coal-fired plants, require large volumes of freshwater which has significant implications on local water resources. However, these problems are often overlooked in the Chinese national energy plans [32]. Without assessing the life-cycle impacts, it makes the net carbon effects uncertain, in particular the unintended consequences on water consumption of each energy production technology.

3. Materials and methods

LCA is one of the most widely used methods for quantifying the environmental impacts of a given product throughout its entire life cycle [33,34]. There are three methodological variants of LCA: Process Life Cycle Analysis (PLCA), Input–Output based Life Cycle Analysis (IO–LCA) analysis and hybrid LCA. PLCA has often been employed to establish the indirect environmental impacts associated with production processes. However, this method can lead to significant truncation errors in the calculations due to an artificial cut-off when defining the system boundaries [35,36]. The limitation of PLCA has led to the use of a combined IO and LCA analysis. Whereas LCA is a bottom-up approach based on individual processes, input–output analysis is a top-down approach, which represents monetary flows between sectors and is able to capture environmental flows between economic sectors by transforming monetary flows to physical flows [34,36]. The advantage of IO–LCA is the completeness of system boundaries since the entire economic activities of a nation state or the global economy are represented. However, the shortcomings of this method include aggregation and allocation errors [33,34,36,37]. Combining the strengths of PLCA and IO–LCA, hybrid analysis methods for LCA have successfully been applied in numerous studies [38–40]. In this study, we applied the integrated hybrid LCA developed by Suh and Huppes [34], which integrate process-based LCA and the IO–LCA methods.

3.1. Process-based LCA

An initial approach to completing a LCA is a process-based LCA method. Process-based LCA calculates the amount of commodities required to produce a certain functional unit (1 kWh electricity in this study). Life Cycle Inventory (LCI) is the data collection phase of an LCA, involving the compilation and quantification of inputs and outputs for a given product system throughout its life cycle [41]. Heijungs [42] first introduced the matrix inversion method to LCI computation [34]. In Heijungs's study, an inventory problem is solved by a system of linear equations, which can be denoted by a $m \times n$ matrix with m commodities and n processes. We define $A_{cp}=a_{ij}$ as a LCA technology matrix, which shows inflows (recorded as negative values) and outflows (recorded as positive values) of commodity i of process j for a certain duration of process operation [43]. The assumption is that processes at stake are being operated under a steady-state condition, which means the selection of a specific temporal window for each process does not change their efficiency [34]. For convenience, a column vector S is used as scaling factor [43], which indicates the required factor of scaling each process to produce the required net output of the system. Therefore, commodity net output of the systems f_p is given by

$$A_{cp}S=f_p \tag{1}$$

Eq. (1) shows that the amount of a commodity delivered to a consumer outside the system is equal to the amount of commodities produced minus the amount used within the system. Therefore, Eq. (1) can be re-arranged to calculate the scaling factor (Supplementary material, Eq. (2))

$$S= A_{cp}^{-1}f_p \tag{2}$$

To calculate the emissions and water consumption, we define a vector $E_p=\{e_j\}$ which contains element e_j that shows CO_2 emissions or water consumption incurred by process j during the operation that a_j is specified for, where a_j is a vector of inputs and output by process j. The total direct and indirect carbon emissions and water consumption required by the system to deliver a commodity is calculated by

$$G_p=E_pA_{cp}^{-1}f_p \tag{3}$$

where G_p is a vector of the total direct and indirect carbon emissions, and f_p is a vector that is defined as the functional unit of the system.

3.2. IO-based LCA

All the processes in an economy are directly or indirectly linked with each other. However, process-based LCA is always truncated to a certain degree as the system boundary is not complete and where the upstream emissions are not captured. Thus, to deal with this system boundary problem, many researchers have used IOA to conduct LCAs, as IOA has the advantage of depicting the entire national economy including all processes (at an aggregate level) [16,44–46].

IOA originally developed by Leontief describes how sectors are inter-related through producing and consuming intermediate economic outputs that are represented by monetary transaction flows between economic sectors, which can be transformed to physical flows such as carbon emissions under the assumption that all outputs of a sector are produced with the same physical flow intensity [47]. In an input–output (IO) model, it is assumed that each industry consumes outputs of various other industries in fixed ratios in order to produce its own unique and distinct output [34,47].

Based on this assumption, we define a $n \times n$ matrix, A_{ss}, of which each column of A_{ss} shows domestic and imported intermediate economic outputs in monetary values which are required to produce one unit of monetary output of another sector; s represents economic sector. We define x as the total economic output where x is equal to the summation of the economic outputs consumed by intermediate economic sectors final consumers (e.g. household, government, capital investment and export). For the

economy as a whole, the IO model can be shown by

$$x = A_{ss}x + f_{IO} \tag{4}$$

where f_{IO} denotes final demand. The total economic output x required to satisfy final demand is calculated by

$$x = (I - A_{ss})^{-1} f_{IO} \tag{5}$$

where I denotes the $n \times n$ identity matrix.

The total direct and indirect emissions by domestic and import sectors to deliver a certain amount of economic output can be calculated by the environmentally extended input–output (EIO) model which assumes that the amount of emissions generated by a sector are proportional to the amount of output of the sector, thus the emissions per unit of sectoral output are fixed. E_{IO}, is defined as a vector which shows the amount of CO_2 emissions or water consumption incurred to produce one monetary unit output of each economic sector. Therefore, the total direct and indirect emissions and water consumption are calculated by

$$G_{IO} = E_{IO}(I - A_{ss})^{-1} f_{IO} \tag{6}$$

where G_{IO} is the total domestic direct and indirect CO_2 emissions and water consumption, and f_{IO} is a vector that shows the net economic outputs of the system.

3.3. Integrated hybrid LCA

In process-based life-cycle approaches, a boundary is drawn around the main inputs and their production processes. Integrating the bottom-up process analysis into a top-down IOA accounts for interactions between the energy sector(s) and the rest of the economy more comprehensively [39,40]. The environmental impacts of a unit production of electricity include all impacts along the entire supply chain such as impacts from extraction of materials, transportation, manufacturing, construction, installation, operation and maintenance, distribution and transformation, and dismantling and disposal. In this study, we construct an integrated hybrid analysis framework to calculate the embodied CO_2 emissions and water consumption for eight electricity generation technologies in China. In this framework, the IO table is interconnected with the matrix representation of the physical production system at upstream and downstream cut-offs.

The general formula of the integrated hybrid model is depicted in Eq. (7).

$$G_{HL} = \begin{bmatrix} \widehat{E_p} & 0 \\ 0 & \widehat{E_{IO}} \end{bmatrix} \begin{bmatrix} A_p & -C_d \\ -C_u & I - A_{IO} \end{bmatrix}^{-1} \begin{bmatrix} f_p \\ 0 \end{bmatrix} \tag{7}$$

where G_{HL} denotes total life-cycle emissions; E_p denotes a diagonal of environmental vector of processes; E_{IO} is a diagonal environmental vector of input–output sectors; A_p refers to the full process matrix with 3931 products by 3931 processes; A_{IO} is a matrix of technical coefficients of the latest Chinese input–output table in 2007; Matrix C_u denotes upstream cut-off flows to the LCA system, linked with the relevant economic sector in IO table, and matrix C_d represents downstream cut-off flows to the IO system from the LCA system and under certain assumptions, C_d can be set to zero [48]; f_p is functional unit in kWh. Each element of C_u has a unit of monetary value per functional unit and each element of C_d is in a unit of physical unit per monetary value. The integrated hybrid LCA can model the full interactions between individual processes and industries in a coherent way.

3.4. Water stress index

Water is a regional issue. There is a well-known regional disparity of water resources in China: the water abundant South vs. water scarce North. In this study, we use a water stress index (WSI) to identify water scarcity at provincial level. WSI is commonly defined as the ratio of total annual freshwater withdrawal to hydrological availability [49]. Pfister et al. (2009) advanced the water stress concept to calculate a WSI, ranging from 0 (no stress) to 1 (maximum stress) (see Pfister et al. [50] for the detailed descriptions of the index). The WSI is used in a number of water studies [51,52] following the draft ISO 14046 standard [53]. Other indicators for assessing water scarcity do exist [54], but they have lower spatial resolution. In this study, we applied Pfister et al.'s method to calculate WSI for each province in China. The WSI was initially obtained at 10 km grid cell and we computed the provincial WSI from the average value of the grids within the provincial boundary.

3.5. Data

3.5.1. Process data

The 2009 Ecoinvent database version 2.1 was used to construct the process analysis LCI (http://www.ecoinvent.org). The Ecoinvent database contains LCI data of about 4000 processes, products and services. The process matrix contains 3931 processes and 3945 products. In the 2009 database, 14 products that had no correspondence with any process were removed from the original matrix to derive a 3931 by 3931 dimensional process matrix. The process matrix is referred to as A_p in Eq. (1). This database includes China's electricity generation data for coal, nuclear and biomass. The calculation of power generated from coal was based on two reference plants with 100 MW and 500 MW, which have a share of 10% and 90%, respectively. Power from nuclear was based on a nuclear power plant with a 1000 MW pressure water reactor. Energy from biomass was based on a co-generation unit with a capacity of 6400 kW and by burning sweet sorghum stems. In terms of wind power, 6469 wind turbines were installed in China by the end of 2007, with the total generation capacity of 5.9 GW and an average wind turbine size of 912 kW [55]. Therefore, a similar size of wind turbines with 800 kW is chosen given that onshore wind farms are seen as having the largest potential in China. In addition, there is no process data for electricity generation from oil, natural gas, hydro, and photovoltaic power plants. In this study, we use the best available LCA data in Ecoinvent to represent electricity generation technologies in China. For natural gas, there are two sizes of power plants in the Ecoinvent database, 100 MW and 300 MW, respectively. In this study, we select the 300 MW natural gas power plants, because the recently installed natural gas power plants were relatively large (more than 1000 MW). There is only one oil power plant (550 MW) in Ecoinvent database [56], which is selected in this study. For hydropower electricity, there is only a mix of run-of-river power plants in Europe available in the database. Electricity from solar photovoltaic (PV) power plant is 3 kW based on electricity production with grid-connected PV power plants mounted on buildings with slanted roof in Switzerland.

3.5.2. IO data

The National 2007 IO table for China is used in this study. The IO table was collected from the National Statistical Bureau of China [57]. The Chinese IO table for 2007 contains 135 economic sectors, is the latest IO table published by the Chinese government.

3.5.3. Upstream requirement matrix

The upstream requirement matrix refers to the C_u matrix in Eq. (1). To construct this matrix, we followed the procedure described in Wiedmann et al. [39] with China-specific data: First, we create a concordance matrix between Ecoinvent processes and IO sectors. The concordance matrix was set up with 135 rows representing all sectors in the IO table and 3931 columns representing processes in the process matrix. Matching processes and sectors are

indicated by ones in the matrix; otherwise, cells are marked as zeros. Second, we established unit prices for Ecoinvent processes. The unit prices of products were assigned based on China Price Yearbook 2008 [58]. Third, we created a technical coefficient matrix matching the process matrix. We used the concordance matrix to populate columns of the designated upstream requirement matrix C_u with technical coefficients from the national IO table. Technical coefficients a_{ij} from the IO table were placed into cell a_{ik} of the matrix where i is an economic sector and j is the economic sectors matching product/process k. Fourth, we multiplied columns of the matrix from step 3 by the unit price p_k of the corresponding Ecoinvent products to yield price-weighted coefficients. Fifth, those upstream inputs in the matrix C_u were removed to avoid double-counting. It is due to the fact that they have already been included in the process matrix.

3.5.4. Environmental data

The Ecoinvent database contains environmental data, such as CO_2 emission and water consumption, for Ecoinvent processes [57]. We directly adopted the CO_2 emission data from the Ecoinvent database for our calculation. However, the water data in the Ecoinvent database refers to water withdrawal data and there is no water consumption data. According to China Environmental Yearbook 2007 [59], we adopted the assumption of a 30% conversion rate from water withdrawal to water consumption for all industrial processes. Direct water consumption per kWh for hydropower plants based on evaporation is determined based on US Department of Energy (2006) [60] due to lack of the data in China. CO_2 emission intensities for input–output sectors were calculated by dividing the sectoral emissions by sectoral economic output. Sectoral CO_2 emissions were calculated from combustion of fuels and industrial processes using the Intergovernmental Panel on Climate Change (IPCC) reference approach [61]. Fossil fuels combustion data at sectoral level were collected from China Energy Statistical Yearbook 2008. Sectoral water withdrawal data were collected from China Economic Census Yearbook 2008.

3.6. Data uncertainty

There are data uncertainties that need to be mentioned in this study. First, the IO table used in this study is in 135 × 135 sectors. Despite this great level of detail, there are still many dissimilar commodities aggregated into the same category and assumed identical with regards to production inputs. However, it provides a comprehensive framework and complete system boundaries to capture the upstream emissions and water consumption. Second, the LCA data for electricity generation from the Ecoinvent database are based on the power plant constructed in the past, which might not reflect current technology, in terms of size and efficiency. However, it is the best data available. Third, the Ecoinvent database only contains LCA data of electricity generation from coal, nuclear and biomass power for China. Therefore, we use the LCA data available from Ecoinvent for other countries to represent electricity generation technologies of natural gas, oil, wind, hydro, and solar in China. This may lead to an increase in uncertainty. To best present Chinese technology, electricity inputs for all production process in the process matrix was replaced by the Chinese electricity production mix due to the fact that electricity is the essential input to the production of most goods and is crucial in term of both CO_2 emissions and water consumption. Therefore, all the electricity consumed in the processes reflects electricity generation in China.

To assess the uncertainty range of the results from this study, we collected the life-cycle CO_2 emissions and water consumption for different electricity generation technologies from various studies in the literature. Based on this, we created error bars on the top of our results to show the differences between our findings and other studies in the literature.

4. Results

4.1. Total life-cycle CO_2 emissions

Life-cycle CO_2 emissions of electricity produced by different energy generation technologies, which are ranked in high-to-low order, are presented in Fig. 2. In addition, an error bar for each generation technology is shown in the figure based on the results from previous studies. Our results show that the total life-cycle CO_2 emissions from fossil fuel based electricity production are significantly higher than the total life-cycle CO_2 emissions from renewable energy, particularly due to the lower emissions during the operation of the power plant (shown as direct emissions). Electricity generated from (pulverized) coal produces the highest amount of CO_2 emissions per kWh (1230.0 g per kilowatt-hour (g/kWh),

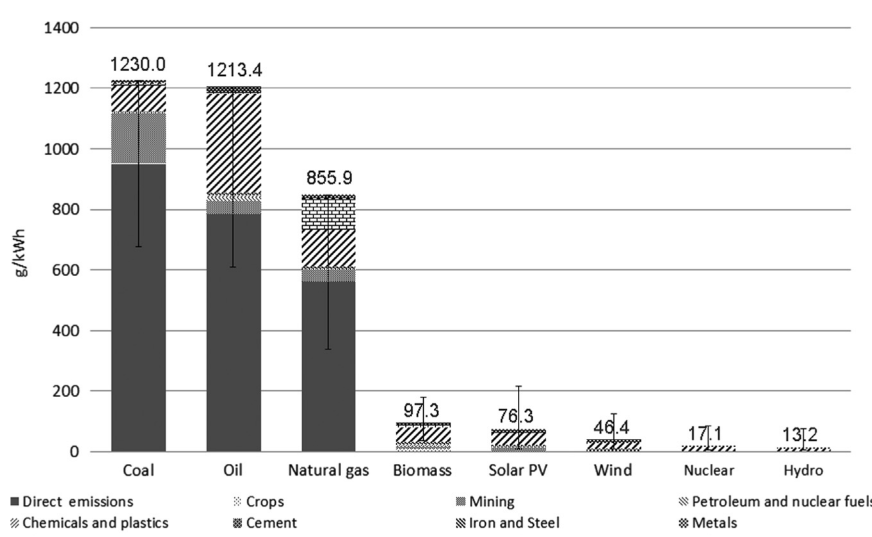

Fig. 2. The total life-cycle CO_2 emission of eight electricity generation technologies in China from 2000 to 2010 (g/kWh). Note: 1 kWh is used as the functional unit to compare different electricity generation technologies. Note: the error bars are based on the results from the literature; for example, coal [62–68], oil [65,69–71], natural gas [8,67,72], biomass [64,73–76], solar PV [65,77–88], wind [16,39,44,65,68,89–99], nuclear [68,99–107], and hydro [65,108–112] (A full list of the literature used in this study can be found in Appendix A).

followed by oil based electricity generation (1213.4 g/kWh) and natural gas (855.9 g/kWh, which is about 30% lower than the emissions from coal and oil). Switching electricity generation from fossil fuels to renewable energy sources could reduce the total life-cycle CO_2 emissions by more than 79% in emissions per kWh. For instance, emissions from electricity produced by hydropower, wind, solar PV and biomass are within a range of 13.2–97.3 g/kWh. Hydro (13.2 g/kWh) has the lowest total emissions while nuclear power takes second lowest place (17.1 g/kWh).

Sources of emissions vary substantially across different types of energy production technologies. For coal-based electricity production, about 78% of emissions have resulted from coal combustion while indirect emissions are caused by fuel combustion in mining and electricity generation for own consumption, which account for 13% and 7% of total emissions, respectively. For oil based electricity production, the share of the direct life-cycle emissions during the electricity production processes is about 65%, which is lower than coal based power generation. Among the eight electricity generation technologies, electricity generated by natural gas has a relatively large share (12% of total emissions) of transport-related emissions due to large volumes of natural gas burned in compressor stations which help the transport of natural gas from extraction sites to power plants. Non-fossil fuel based electricity technologies have much lower total carbon emissions and even their indirect emissions from upstream processes are much lower. The higher indirect emissions of fossil fuel based electricity generation are mainly due to the large emissions from mining and the demand of electricity during mining and operation of the power plant. However, non-fossil fuel based technologies require less inputs for mining and operation, thus tend to have lower indirect emissions as well. For non-fossil fuel based technologies, upstream processes play a major role in contributing to the total life-cycle CO_2 emissions. For instance, in the case of wind power generated electricity, electricity consumption during upstream production processes contributes 43% of the total life-cycle CO_2 emissions, while steel, cement, and chemicals and plastics contribute 12%, 5%, and 3%, respectively. In the case of hydropower, cement contributes 24% of total life-cycle CO_2 emissions.

In this study, CO_2 emissions per kWh for fossil fuel based electricity generation technologies such as coal, oil, and natural gas are higher than the results from other studies (see error bars in Fig. 2). Three factors may explain these differences: First, most LCA studies for fossil fuel based power generation use the process-based LCA approach e.g. [62,63,64–67,69,72], which mainly captures direct emissions during the production processes and some emissions from upstream production depending on the system boundary. For example, in Odeh's study on LCA of UK's coal fired power plants, direct emissions from coal combustion accounted for 89% of the total life-cycle CO_2 emissions compared with 78% in this study. The main reason is that our study uses a hybrid LCA with a more complete system boundary (i.e. the entire national supply chains) capturing both emissions from power plant operations and upstream production (see Suh and Huppes (2005) [34] and Wiedmann (2011) [39] for details). In fact, the direct emissions from fossil fuel based technologies in this study are fairly close to the emissions presented in the literature based on process-based LCA as shown in Fig. 2, such as coal (950 g/kWh vs. 902 g/kWh in average), oil (790 g/kWh vs. 772 g/kWh), and natural gas (560 g/kWh vs. 450 g/kWh). Therefore, the differences are mainly due to the indirect emissions. Second, a high percentage of fossil fuels in China's fuel mix lead to a large amount of indirect emissions caused upstream. This is also reflected in the results from this study that indirect emissions account for more than 20% of the total life-cycle emissions for fossil fuel based generation technologies, mainly from electricity input, transportation, mining, iron and steel. However, other studies focused on the UK [8,113], US [63,64], Japan [65], and other countries [66,67], are with better fuel mix and thus lower upstream CO_2 emissions. Third, most LCA studies in the literature focused on developed countries which may have much higher energy efficiency in their electricity generation sector. Thus, their CO_2 emissions per unit of electricity are lower than China's.

4.2. Total life-cycle water consumption

Electricity generation requires huge amounts of water, which can put substantial pressures on water resources and ecosystems, and is particularly important in water scarce regions such as North China. Fig. 3 depicts the total life-cycle water requirements for the eight electricity generation technologies. Total life-cycle water

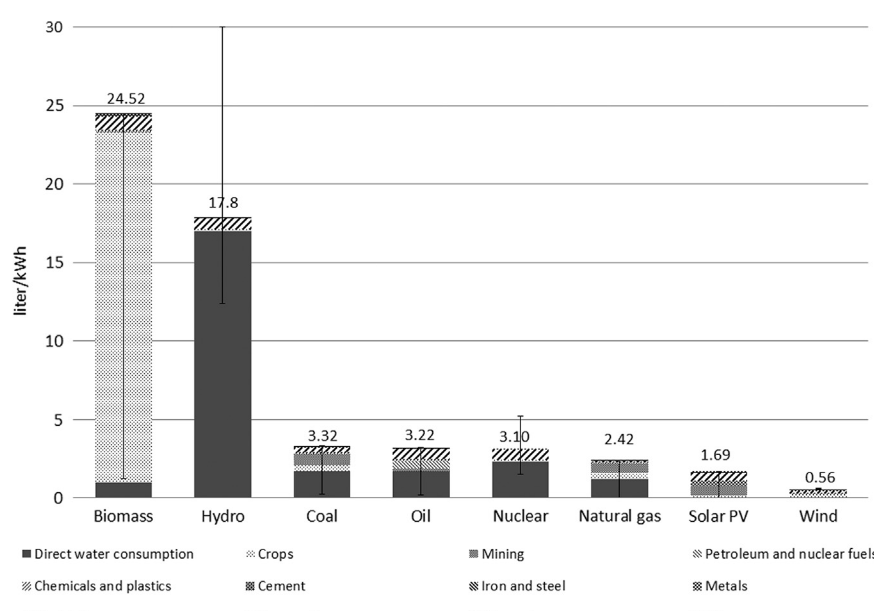

Fig. 3. Total life-cycle water requirements for the eight major electricity generation technologies in China (l/kWh). Note: the error bars are based on the results from the literature: hydro [60,114], thermal electric [114,115], coal [116,117], natural gas [116,117], solar PV [60], and wind [16]. (A full list of the literature used in this study can be found in Appendix A).

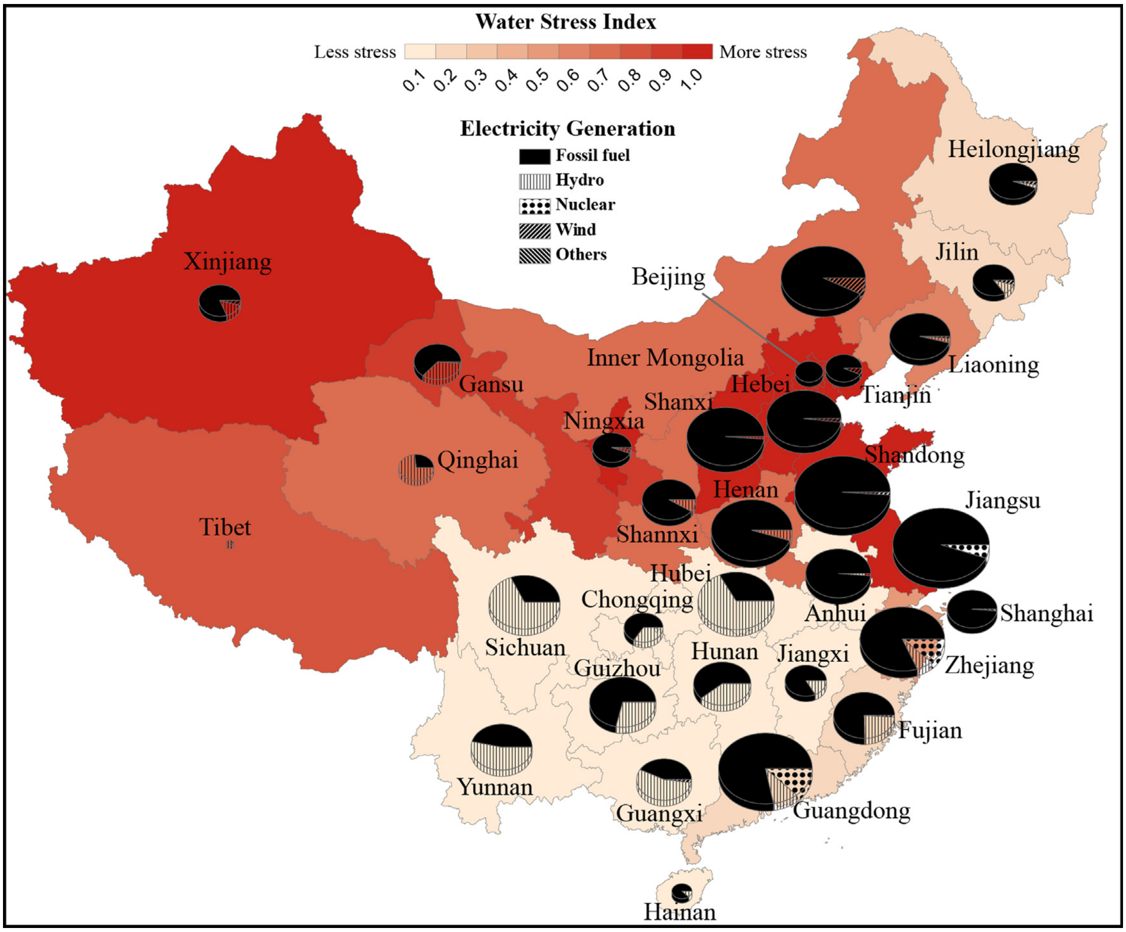

Fig. 4. China's regional electricity fuel mix and degree of water stress in 2010. The size of the pie chart reflects the amount of electricity production. Background colors of the map show WSI ranging from severe water stress regions in red color to less water stress in pink color. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

consumption is referred to as the net amount of water (i.e. water withdrawal minus water discharge) consumed along the supply chain to produce 1 kWh of electricity. The findings show that biomass power generation ranks first (24.52 l/kWh); and crop production accounts for 95% of its total water consumption. Hydropower ranks second (17.8 l/kWh) in terms of total life-cycle water requirements; water evaporation in reservoirs accounts for most of its water consumption. Thermoelectric production technologies such as coal, oil, natural gas and nuclear are at a similar range, with total life-cycle water requirements between 2.42 l/kWh and 3.32 l/kWh, of the total. While electricity from solar PV generation requires about half the water (1.69 l/kWh) per unit of electricity output compared with thermoelectric energy production; wind power consumes the least amount of water (0.56 l/kWh) among all investigated electricity generation technologies.

Fig. 3 also shows that in thermoelectric-based energy generation technologies (e.g. coal, oil, natural gas and nuclear power), direct water consumption attributes 50–74% of the total life-cycle water requirements. For solar PV and wind power, electricity production requires most water for supporting upstream processes. For example, mining, electricity, and metals accounts for 35%, 31%, and 17% of life-cycle water consumption, respectively, for solar PV, and wind powered electricity requires water from agriculture (40%), electricity (21%) and metals (5%).

Fig. 3 shows that the uncertainties of LCA water consumption are extremely large for biomass due to differing climatic conditions and fossil fuels mainly due to differences in cooling technologies. For example, power plants with air cooling systems may potentially require up to 50% less total life-cycle water inputs compared to once-through and recirculating systems [60]. However, air cooling systems are still not commonly used in China. Although air cooling may significantly reduce direct water consumption for thermal power plants, their indirect water consumption for inputs such as mining and coal washing, is still significantly larger than for wind electricity. For example, the indirect water consumption of electricity from coal is 1.6 l/kWh, which is almost three times the total life-cycle water consumption from wind power. There are also large differences in total water consumption of electricity from biomass between this study and studies in literature. This is mainly due to the systems boundary cut-off, as other studies only took direct water consumption into account while indirect water consumption, such as water consumption in agricultural production, was neglected. For wind power, our calculation is slightly lower than the finding from Li et al. [16], which may be due to using different methods. Li et al. (2012) applied an IO-based LCA, while this study used an integrated hybrid LCA approach.

5. Discussion

Coal is by far the dominant energy source in China's electricity fuel mix because of its low costs. On the other hand, among all energy generation technologies, coal-fired electricity not only ranks highest for total life-cycle CO_2 emissions with 1230 g/kWh,

but also requires 3.32 l of water during the entire life-cycle to generate 1 kWh of electricity potentially exerting considerable pressure on water resources particularly in water scarce areas of China.

Fig. 4 shows China's regional fuel mix in electricity generation and WSI. Fossil fuel based electricity (i.e. to 97% based on coal) accounts for more than 90% of the power supply in most regions of North China where water is also of limited supply. Additionally, for coal-fired electricity generation, direct water consumption ranks the highest and accounts for 52% of its total life-cycle water consumption, making it a significant stressor on local water resources in addition to agricultural water consumption; its effects are particularly important to highly water stressed areas such as Inner Mongolia and Shanxi, with electricity mainly generated by coal-fired plants. A significant share (more than 20%) of total electricity generation gets exported to surrounding regions, such as Beijing, Hebei, and Liaoning. Hence, reducing coal-fired electricity generation or switching to air cooling system can mitigate water stress in these electricity exporting regions.

This study shows that wind power electricity generation can potentially save more than 79% life-cycle CO_2 emissions and potentially consume up to 83% less water than fossil-fuel based electricity such as coal. Despite very high uncertainties of water consumption of thermal power plants due to differences in cooling technologies, one can conclude that it is particularly important to water stressed areas in China such as North China to reap the dual benefits of lower carbon emissions and water consumption by switching from traditional, fossil-fuel based to renewable electricity generation. There is ample potential for producing renewables in many parts of china. For example, a report by the Global Wind Energy Council (GWEC) [118] concluded that the technically exploitable capacity of wind energy is around 600–1000 gigawatts on land in China, which is enough to allow wind playing a major part in China's future energy mix. These wind resources are largely available in northern China where water is scarce (see Supplementary material Fig. S1). Thus, there is a huge potential for the northern provinces such as Inner Mongolia, Ningxia, Shanxi, Hebei, Gansu, and Xinjiang to develop wind power. Based on China's wind power development plans [119], our calculations show that by 2020 Inner Mongolia could potentially save annually up to 179 MT CO_2 (i.e. 44% of Inner Mongolia's total CO_2 emissions in 2008) and 418 million m^3 (Mm^3) water (18% of its industrial water use).

As shown in our findings, solar PV is another technology that has the potential for significantly reduced total life-cycle CO_2 emissions per unit of electricity production. Nonetheless, solar PV does not have the same advantage as wind power to reduce water consumption. Also, there are many other issues that need to be addressed before solar PV can play a major role in China's future electricity fuel mix. These issues include a shortage of the supply of silicon material, rising cost of raw materials, low efficiency and environmental issues such as pollution (i.e. acidic and alkaline waste water and heavy metal waste residues) [120].

Carbon capture and storage (CCS) has been a very prominent subject in the climate debate over the last few years [121]. Odeh and Cockerill (2008) showed that pulverized coal with CCS could lead to a 72% of CO_2 emission reduction [8]. However, it is an energy intensive process which may reduce the overall efficiency of the power plant [8]. Furthermore, there are issues of financing adequate transport infrastructure and permanent storage [122]. Although CCS can help to reduce CO_2 emissions, it consumes more water per kWh electricity due to the decline in efficiency of the power plant CCS causes. Therefore, it is vital to take water consumption and other factors into account when developing CCS.

As shown in Fig. 4, hydropower plays a significant role in electricity production in the south and south-west of China because of abundant water resources in these regions. For example, hydropower electricity contributes more than half to total electricity production in Hubei, Yunnan, and Sichuan. There are a number of environmental issues associated with hydropower plants [123,124], as well as social issues [125], which could further be exacerbated through extensive large-scale projects. Many studies emphasized that “small” hydropower is a source of clean energy with little or no adverse environmental impacts [126,127]. However, an extensive use of this technology may lead to higher environmental degradation than that caused by large hydropower [128].

Nuclear power has also much lower CO_2 emissions per kWh than fossil-fuel based energy generation technologies. However, nuclear power plants generally require large water inputs for cooling processes, which is reflected in their site locations such as the coastal regions Guangdong and Zhejiang and to a lesser extent in Jiangsu (see Fig. 4). Therefore, the development of nuclear energy in China is not sustainable in terms of water consumption, particularly if a large number of nuclear power plants are deployed in inland or North China. Moreover, disposal and storage of nuclear waste and potential hazards have been criticized for decades [129]. With less than 1% of the global uranium reserves located in China [130], the over-dependence on nuclear power would compromise national energy security, which is inconsistent with the principle of safeguarding energy security stated in China's Mid-Long Term Development Plan for Nuclear Power [22].

Failure to incorporate both water and climate implications of energy policies can potentially lead to serious and unexpected side effects such as water scarcity. Increasing the share of renewable energy in China's electricity fuel mix could not only curb CO_2 emissions, but also reduce the pressure on the local environment especially in already water scarce regions. Therefore, water availability should play a much larger role in China's energy plan than it currently does. Even if non-coal energy generation technology were significantly more expensive than coal-based technology, renewables might be more cost-effective when considering lower impacts on local water resources, in particular in water scarce areas such as in north and north-east China.

Acknowledgment

We thank Dr. Stephan Pfister for providing water stress index data.

Appendix A

See Table A1–A7 here.

Table A1
Coal, oil and natural gas. Life-cycle emissions of electricity from coal are between 676 g-CO_2-e/kWh and 1042 g-CO_2-e/kWh with an average of 902 g-CO_2-e/kWh across the world. Natural gas combined cycle (NGCC) power plants cause an average of 450 g-CO_2-e/kWh across the world in the range of 337–499 g-CO_2-e/kWh. The world average of life-cycle emissions for electricity generation from oil is about 772 g-CO_2-e/kWh in the range of 608 and 932.

Power plant	Location	Study	Gross output MW	Capacity factor	Life time	g CO_2/kWh
Coal	US	[63]	360	60	30	1042
Coal	US	[64]	600	–	–	847
Coal	US	[68]	1000	75%	40	974
Coal	Japan	[65]	1000	70%	30	975.2
Coal	Germany	[67]	700	–	–	676
Coal	UK	[62]	660		30	990
Coal	UK	[8]	453	75%	–	879
Coal	Netherlands	[66]	600	–	30	837
Oil	Japan	[71]	1000	–	–	755.7
Oil – existing peak load power station	UK	[69]	527.9	–	–	823
Oil – Combined cycle base load plant	UK	[69]	527.9	–	–	608
Oil	Singapore	[70]	250	70%	25	932
Oil	Japan	[65]	1000	70%	30	742.1
NGCC	US	[81]	620	–	–	466
NGCC	US	[64]	600	–	–	499
NGCC	Germany	[67]	700	–	–	337
NGCC	UK	[8]	500	75%	30	488
NGCC	Norway	[72]	400	–	25	459

Note: IGCC=coal-based integrated gasification combined cycle and NGCC=natural gas combined cycle.

Table A2
Nuclear. The average life-cycle emissions for LWR, PWR and BWR are 28.35 gCO_2/kWh, 16.69 g-CO_2/kWh and 19.39 g-CO_2/kWh, respectively.

Power plant	Location	Study	Gross output MW	Load factor	Life time	g-CO_2/kWh
PWR	Japan	[107]	1000	–	30	34
LWR	Germany	[105]	1300	77.6	20	5
LWR	Germany	[105]	1300	77.6	20	21
LWR	Germany	[105]	1300	77.6	20	28
LWR	Germany	[105]	1300	77.6	20	84
BWR	Japan	[104]	1000	70	30	21.6
BWR	Japan	[104]	1000	70	30	26.4
BWR	Japan	[104]	1000	70	30	37
PWR	Japan	[104]	1000	70	30	24.7
PWR	Japan	[104]	1000	70	30	31.4
PWR	Belgium	[99]	1000	86.8	40	1.8
PWR	Belgium	[99]	1000	86.8	40	4
PWR	US	[68]	1000	75	40	15
LWR	Switzerland	[106]	1000	70	40	8.88
LWR	Switzerland	[106]	1000	70	40	8.92
BWR	Japan	[106]	1000	75	30	8.93
BWR	Japan	[106]	1000	75	30	10.18
BWR	Japan	[106]	1000	75	30	19.41
BWR	Japan	[106]	1000	75	30	20.93
PWR	France	[102]	1000	81.4	40	5.95
BWR	Germany	[102]	1000	81.4	40	10.7
AGR	UK	[100]	1250	–	34	5.05
AGR	UK	[101]	1250	–	34	6.85[a]
LWR	US	[103]	1000	85	40	17
LWR	US	[103]	1000	85	40	54

Note: AGR=advanced gas-cooled reactor; LWR=light water reactor; HWR=heavy water reactor; PWR=pressurized water reactor and BWR=boiling water reactor.

[a] For future projection.

Table A3
Hydropower. Small hydropower plants have smaller emission factors of about 40 g-CO_2-e/kWh on average, while large hydro tends to have much lower emission intensity.

Power plant	Location	Study	Gross output kW	Life time	g-CO_2/kWh
Small Hydro	Japan	[65]	10,000	30	11.3
Small Hydro	Japan	[108]	10,000	30	18
Small Hydro	Japan	[109]	10,000	30	17.6
Small Hydro	India	[110]	50	30	74.88
Small Hydro	India	[110]	100	30	55.42
Small Hydro	India	[111]	3000	30	35.29
Small Hydro	India	[111]	250	30	35.35
Small Hydro	India	[111]	1000	30	42.95
Small Hydro	India	[111]	400	30	33.87
Small Hydro	India	[111]	2000	30	31.2
Small Hydro	India	[111]	1000	30	62.4
Large Hydro	Sweden	[112]	–	–	6

Table A4
Wind. The global average emission factor of onshore wind power plants is about 30 g-CO_2-e/kWh.

Power plant	Location	Study	Power rate kW	Capacity factor	Life time	g-CO_2/kWh
Wind	Japan	[97]	100	31.5%	20	71.7
Wind	Japan	[98]	100	31.5%	20	95.6
Wind	Japan	[96]	100	40%	20	123.7
Wind	UK	[94]	6600	–	20	25
Wind	Argentina	[91]	2.5	22%	20	42
Wind	US	[68]	25	24%	25	15
Onshore	Denmark	[95]	500	25.1%	20	9.7
Offshore	Denmark	[95]	500	28.5%	20	16.5
Wind	Belgium	[99]	600	34.2	20	7.9–9.2
Wind	Japan	[92]	100	34.8%	25	39.4
Wind	Japan	[65]	300/400	20%	30	20.3–29.5
Wind	Canada	[90]	500	–	20	40.6
Onshore wind	Germany	[44]	500	–	20	45–77
Onshore wind	Brazil	[44]	500	–	20	26
Onshore	Germany	[93]	1500	–	–	11
Offshore	Germany	[93]	2500	–	–	9
Onshore wind	Switzerland	[89]	800	–	20	11
Offshore wind	Switzerland	[89]	2000	–	20	13
Offshore	UK	[39]	2000	30%	20	30.2
On shore	China	[16]	800	30%	20	69.9

Table A5
Solar PV. Life-cycle emissions are quite variable between 9.4 and 217 g-CO_2-e/kWh, depending on whether a binary or open cycle plant is used, and on whether new geothermal vents are created during field exploration. A global average of mixed solar power has an emission factor of 63.91 g-CO_2-e/kWh.

Type of cell	Location	Study	Power rating kW	Life time	g-CO_2/kWh
Amorphous solar PV	Netherlands	[82]	30 m^2	20	47
Mono-crystalline solar PV	Japan	[79]	3	20	91
Amorphous solar PV	Netherlands	[77]	3300	–	50
Nano-crystalline dye sensitized system	Sweden	[78]	–	20	19–47
Mono-crystalline solar PV	India	[80]	0.035	20	64.8
Poly-crystalline solar PV	China	[84]	100	30	12
Poly-crystalline solar PV	Japan	[65]	3	30	53.4
Poly-crystalline solar PV	Greece	[88]	3	–	104
Mono-crystalline solar PV	Singapore	[85]	2.7	25	217
Mono-crystalline solar PV	Singapore	[85]	2.7	25	165
Mono-crystalline solar PV	UK	[86]	14.4	30	44
Amorphous solar PV	US	[81]	8	30	39
Amorphous solar PV	China	[83]	100	30	15.6
Amorphous solar PV	US	[87]	33	20	34.3
Poly-crystalline solar PV	China	[83]	100	30	9.4
Poly-crystalline solar PV	China	[83]	100	30	12.1

Table A6
Biomass. The average emission factor of biomass is about 80 g-CO_2-e/kWh, in the range between 35 g-CO_2-e/kWh and 178 g-CO_2-e/kWh.

Power plant	Location	Study	Gross output MW	g-CO_2/kWh
90% Hard coal and 10% straw	Germany	[75]	509	37
90% Hard coal and 10% Wood				35
Coal system + biomass co-firing and CO_2 sequestration	US	[64]	457	43
IBGCC + CO_2 removal (chemical absorption)	–	[73]	204.5	178
Biogas cogeneration	Austria	[74]	0.08	78
IGCC	–	[76]	1 MWh	110

Table A7
Water consumption per unit of electricity generation from different energy technologies.

Power plant	Location	Study	Gross output MW	l/kWh
Hydro	U.S.	[60]	–	12.4–30
Thermoelectric	Global	[115]	–	1.5
Thermoelectric	U.S.	[114]	–	1.8
Coal	Australia	[117]	–	2.0–2.2
Coal	U.S.	[116]	–	1.8
Natural Gas	U.S.	[116]	–	0.8
Natural Gas	Australia	[117]	–	1.2
Wind	China	[16]	800 k	0.6
Solar	U.S.	[60]	–	1.5

Appendix A. Supplementary material

Supplementary information associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.rser.2014.07.080.

References

[1] UNFCCC. Copenhagen Accord. FCCC/CP/2009/L7. Copenhagen; 2009.
[2] Su W. Letter from SU Wei Director General of the Department of Climate Change, NDRC, to Yves de Boer, Executive Secretary of the UNFCCC. Department of Climate Change, National Development & Reform Commission of China; 2010.
[3] Bloomberg News. China's Spending on Renewable Energy May Total 1.8 Trillion Yuan. Bloomberg News; 2013.
[4] Wang Q, Chen Y. Status and outlook of China's free-carbon electricity. Renew Sustain Energy Rev 2010;14:1014–25.
[5] Huang H, Yan Z. Present situation and future prospects of hydropower in China. Renew Sustain Energy Rev 2009;13:1652–6.
[6] Levine MD, Price L, Zhou N, Fridley D, Aden N, Lu H, et al. Assessment of China's energy-saving and emission reduction accomplishments and opportunities during the 11th Five Year Plan. Lawrence Berkeley National Laboratory, Berkeley; 2010.
[7] Zhou N, Levine MD, Lynn P. Overview of current energy-efficiency policies in China. Energy Policy 2010;38:6439–52.
[8] Odeh NA, Cockerill TT. Life cycle GHG assessment of fossil fuel power plants with carbon capture and storage. Energy Policy 2008;36:367–80.
[9] National Bureau of Statistics of China. China economic census yearbook 2008. Beijing: National Bureau of Statistics of China; 2008.
[10] Jiang Y. China's water scarcity. J Environ Manage 2009;90:3185–96.
[11] Mo W, Nasiri F, Eckelman MJ, Zhang Q, Zimmerman JB. Measuring the embodied energy in drinking water supply systems: a case study in the great lakes region. Environ Sci Technol 2010;44:9516–21.
[12] Cooper DC, Sehlke G. Sustainability and energy development: influences of greenhouse gas emission reduction options on water use in energy production. Environ Sci Technol 2012;46:3509–18.
[13] IEA. Water for energy. World Energy Outlook 2012, International Energy Agency, [chapter 17]; 2014.
[14] Kahrl F, Roland-Holst D. China's water-energy nexus. Water Policy, New York 2008;10:51–65.
[15] Glassman D, Wucher M, Isaacman T, Champilou C. The water-energy nexus – adding water to the energy agenda. World Policy Institute; 2011.
[16] Li X, Feng K, Siu YL, Hubacek K. Energy-water nexus of wind power in China: the balancing act between CO_2 emissions and water consumption. Energy Policy 2012;45:440–8.
[17] SERC. China Electricity generation 2012. PR China: State Electricity Regulatory Commission; 2013.
[18] Chen Q, Kang C, Xia Q, Guan D. Preliminary exploration on low-carbon technology roadmap of China's power sector. Energy 2011;36:1500–12.
[19] Kahrl F, Williams J, Jianhua D, Junfeng H. Challenges to China's transition to a low carbon electricity system. Energy Policy 2011;39:4032–41.
[20] Wang T, Watson J. Scenario analysis of China's emissions pathways in the 21st century for low carbon transition. Energy Policy 2010;38:3537–46.
[21] Zhang Z. China in the transition to a low-carbon economy. Energy Policy 2010;38:6638–53.
[22] NDRC. Mid-long term development plan for nuclear power (2005–2010). Beijing: National Development Reform Commission; 2007 [In Chinese].
[23] NDRC. Mid-long term development plan for renewable energy in China. Beijing: National Development Reform Commission; 2007 ([In Chinese]).
[24] Xinhua. The Eleventh Five Year Plan. Xinhua News Agency. Beijing; 2005.
[25] Central Government. China's policies and actions on addressing climate change [中国应对气候变化的政策与行动]; 2008.
[26] Qiu J. China's climate target: is it achievable? Nature 2009;462:550–1.
[27] Bradsher K. China fears warming effects of a rising consumer class. The New York Times; 2010.
[28] State Council. 12th Five Year Plan on Energy Development. State Council of the People's Republic of China; 2013.
[29] WNA. Plans for New Reactors Worldwide. World Nuclear Association; 2011.
[30] IEA. World Energy Outlook 2012. International Energy Agency; 2012.
[31] EIA; International Energy Outlook 2011;Washington D.C.;U.S. Energy Information Administration;2011.
[32] Ji Z, Zhong L, Wen H. Q&A: energy, water, and China's economy. Washington: DC: World Resources Institute; 2012.
[33] Crawford RH. Validation of a hybrid life-cycle inventory analysis method. J Environ Manage 2008;88:496–506.
[34] Suh S, Huppes G. Methods for life cycle inventory of a product. J Clean Prod 2005;13:687–97.
[35] Lenzen M. Differential convergence of life-cycle inventories toward upstream production layers. J Ind Ecol 2002;6:137–60.
[36] Menzies GF, Turan S, Banfill PFG. Life-cycle assessment and embodied energy:a review. Constr Mater 2007;160:135–43.
[37] Lenzen M, Munksgaard J. Energy and CO_2 life-cycle analyses of wind turbines – review and applications. Renew Energy 2002;26:339–62.
[38] Suh S, Lenzen M, Treloar GJ, Hondo H, Horvath A, Huppes G, et al. System boundary selection in life-cycle inventories using hybrid approaches. Environ Sci Technol 2004;38:657–64.
[39] Wiedmann TO, Suh S, Feng K, Lenzen M, Acquaye A, Scott K, et al. Application of hybrid life cycle approaches to emerging energy technologies – the case of wind power in the UK. Environ Sci Technol 2011;45:5900–7.
[40] Acquaye AA, Wiedmann T, Feng K, Crawford RH, Barrett J, Kuylenstierna J, et al. Identification of 'carbon hot-spots' and quantification of GHG intensities in the biodiesel supply chain using hybrid LCA and structural path analysis. Environ Sci Technol 2011;45:2471–8.
[41] ISO 14040. Environmental management – life cycle assessment – principles and framework. Geneva, Switzerland: International Organisation for Standardisation; 1998.
[42] Heijungs R. A generic method for the identification of options for cleaner products. Ecol Econ 1994;10:69–81.
[43] Heijungs R, Suh S. The computational structure of life cycle assessment. Dordrecht, The Netherlands: Kluwer Academic Publisher; 2002.
[44] Lenzen M, Wachsmann U. Wind turbines in Brazil and Germany: an example of geographical variability in life-cycle assessment. Appl Energy 2004;77:119–30.
[45] Cicas G, Hendrickson CT, Horvath A, Matthews HS. A regional version of a US economic input–output life-cycle assessment model. Int J Life Cycle Assess 2007;12:365–72.
[46] Hendrickson CT, Horvath A, Joshi S, Lave LB. Economic input–output models for environmental life-cycle assessment. Environ Sci Technol 1998;32:184A.
[47] Miller RE, Blair PD. Input–output analysis: foundations and extensions. 2nd ed. New York: Cambridge University Press; 2009.
[48] Peters G, Hertwich E. A comment on "fuctions, commodities and environmental impacts in an eclogical-economic model". Program for inudstriell okologi; 2004.
[49] Pfister S, Bayer P, Koehler A, Hellweg S. Environmental impacts of water use in global crop production: hotspots and trade-offs with land use. Environ Sci Technol 2011;45:5761–8.

[50] Pfister S, Koehler A, Hellweg S. Assessing the environmental impacts of freshwater consumption in LCA. Environ Sci Technol 2009;43:4098–104.
[51] Ridoutt BG, Pfister S. A revised approach to water footprinting to make transparent the impacts of consumption and production on global freshwater scarcity. Glob Environ Change 2010;20:113–20.
[52] Ridoutt B, Pfister S. A new water footprint calculation method integrating consumptive and degradative water use into a single stand-alone weighted indicator. Int J Life Cycle Assess 2013;18:204–7.
[53] ISO. ISO/DIS 14046 Water footprint – principles, requirements and guidelines. The International Organization for Standardization; 2013.
[54] Kounina A, Margni M, Bayart J-B, Boulay A-M, Berger M, Bulle C, et al. Review of methods addressing freshwater use in life cycle inventory and impact assessment. Int J Life Cycle Assess 2013;18:707–21.
[55] Shi P. China wind power generation capacity in 2007 China Wind Energy Association; 2008.
[56] Ecoinvent. Ecoinvent database. Swiss Centre for Life Cycle Inventories; 2012.
[57] National Statistical Bureau of China. China provincial statistics yearbook 2008. Beijing: National Statistical Bureau of China; 2008.
[58] National Bureau of Statistics of China. China price yearbook 2008. Beijing: National Bureau of Statistics of China; 2008.
[59] China National Statistic Office. China environmental yearbook 2007. Beijing: China National Statistic Office; 2007.
[60] DOE. Energy demands on water resources. US Department of Energy; 2006.
[61] IPCC. Guidelines for national greenhouse gas inventories. Intergovernmental Panel on Climate Change; 1996.
[62] Odell PR, Cockerill TT. Life cycle analysis of UK coal fired power plants. Energy Convers Manage 2008;49:212–20.
[63] Spath P, Mann M, Kerr D. Life cycle assessment of coal-fired power production. Golden, CO: US National Renewable Energy Laboratory; 1999.
[64] Spath PL, Mann MK. Biomass power and conventional fossil systems with and without CO_2 sequestration – comparing the energy balance, greenhouse gas emissions and economics. National Renewable Energy Laboratory, Berkeley; 2004.
[65] Hondo H. Life cycle GHG emission analysis of power generation systems: Japanese case. Energy 2005;30:2042–56.
[66] Koornneef J, van Keulen T, Faaij A, Turkenburg W. Life cycle assessment of a pulverized coal power plant with post-combustion capture, transport and storage of CO2. Int J Greenh Gas Control 2008;2:448–67.
[67] Viebahn P, Nitsch J, Fischedick M, Esken A, Schüwer D, Supersberger N, et al. Comparison of carbon capture and storage with renewable energy technologies regarding structural, economic, and ecological aspects in Germany. Int J Greenh Gas Control 2007;1:121–33.
[68] White SW, Kulcinski GL. Birth to death analysis of the energy payback ratio and CO_2 gas emission rates from coal, fission, wind, and DT-fusion electrical power plants. Fusion Eng Des 2000;48:473–81.
[69] Berry J, Holland M, Watkiss P, Boyd R, Stephenson W. Power generation and the environment – a UK perspective. Abingdon, Oxfordshire: AEA Technology Environment; 1998.
[70] Kannan R, Tso CP, Osman R, Ho HK. LCA-LCCA of oil fired steam turbine power plant in Singapore. Energy Convers Manage 2004;45:3093–107.
[71] Uchiyama Y, Yamamoto H. Energy analysis on power generation plants. Economic Research Center, Tokyo; 1991.
[72] Singh B, Strømman AH, Hertwich E. Life cycle assessment of natural gas combined cycle power plant with post-combustion carbon capture, transport and storage. Int J Greenh Gas Control 2011;5:457–66.
[73] Carpentieri M, Corti A, Lombardi L. Life cycle assessment (LCA) of an integrated biomass gasification combined cycle (IBGCC) with CO_2 removal. Energy Convers Manage 2005;46:1790–808.
[74] Chevalier C, Meunier F. Environmental assessment of biogas co- or trigeneration units by life cycle analysis methodology. Appl Therm Eng 2005;25:3025–41.
[75] Hartmann D, Kaltschmitt M. Electricity generation from solid biomass via co-combustion with coal: energy and emission balances from a German case study. Biomass Bioenergy 1999;16:397–406.
[76] Rafaschieri A, Rapaccini M, Manfrida G. Life cycle assessment of electricity production from poplar energy crops compared with conventional fossil fuels. Energy Convers Manage 1999;40:1477–93.
[77] Alsema EA. Energy pay-back time and CO_2 emissions of PV systems. Prog Photovolt: Res Appl 2000;8:17–25.
[78] Greijer H, Karlson L, Lindquist S-E, Anders H. Environmental aspects of electricity generation from a nanocrystalline dye sensitized solar cell system. Renew Energy 2001;23:27–39.
[79] Kato K, Murata A, Sakuta K. An evaluation on the life cycle of photovoltaic energy system considering production energy of off-grade silicon. Sol Energy Mater Sol Cells 1997;47:95–100.
[80] Mathur J, Bansal NK, Wagner HJ. Energy and environmental correlation for Renewable Energy systems in India. Energy Sources 2002;24:19–26.
[81] Meier P. Life-cycle assessment of electricity generation systems and applications for climate change policy analysis. Madison: University of Wisconsin; 2002.
[82] Nieuwlaar E, Alsema E, van Engelenburg B. Using life-cycle assessments for the environmental evaluation of greenhouse gas mitigation options. Energy Convers Manage 1996;37:831–6.
[83] Ito M, Kato K, Komoto K, Kichimi T, Kurokawa K. A comparative study on cost and life-cycle analysis for 100 MW very large-scale PV (VLS-PV) systems in deserts using m-Si, a-Si, CdTe, and CIS modules. Prog Photovolt: Res Appl 2008;16:17–30.
[84] Ito M, Kato K, Sugihara H, Kichimi T, Song J, Kurokawa K. A preliminary study on potential for very large-scale photovoltaic power generation (VLS-PV) system in the Gobi desert from economic and environmental viewpoints. Sol Energy Mater Sol Cells 2003;75:507–17.
[85] Kannan R, Leong KC, Osman R, Ho HK, Tso CP. Life cycle assessment study of solar PV systems: an example of a 2.7 kWp distributed solar PV system in Singapore. Solar Energy 2006;80:555–63.
[86] Muneer T, Younes S, Lambert N, Kubie J. Life cycle assessment of a medium-sized photovoltaic facility at a high latitude location. Proc Inst Mech Eng Part A: J Power Energy 2006;220:517–24.
[87] Pacca S, Sivaraman D, Keoleian GA. Parameters affecting the life cycle performance of PV technologies and systems. Energy Policy 2007;35:3316–26.
[88] Tripanagnostopoulos Y, Souliotis M, Battisti R, Corrado A. Energy, cost and LCA results of PV and hybrid PV/T solar systems. Prog Photovolt: Res Appl 2005;13:235–50.
[89] Jungbluth N, Bauer C, Dones R, Frischknecht R. Life cycle assessment for emerging technologies: case studies for photovoltaic and wind power. Int J Life Cycle Assess 2005;10:24–34.
[90] Khan FI, Hawboldt K, Iqbal MT. Life cycle analysis of wind-fuel cell integrated system. Renew Energy 2005;30:157–77.
[91] Nadal G. Life cycle direct and indirect pollution associated with PV and wind energy systems. SC de Bariloche, Argentina: Fundacio´n Bariloche; 1998.
[92] Nomura N, Inaba A, Tonooka Y, Akai M. Life-cycle emission of oxidic gases from power-generation systems. Appl Energy 2001;68:215–27.
[93] Pehnt M. Dynamic life cycle assessment (LCA) of renewable energy technologies. Renew Energy 2006;31:55–71.
[94] Proops JLR. Energy intensities, input–output analysis and economic development. In: Ciaschini M, editor. Input–output analysis – current developments. New York: Chapman and Hall; 1998. p. 201–15.
[95] Schleisner L. Life cycle assessment of a wind farm and related externalities. Renew Energy 2000;20:279–88.
[96] Uchiyama Y. Life cycle analysis of photovoltaic cell and wind power plants. Assessment of greenhouse gas emissions from the full energy chain of solar and wind power and other energy sources. Vienna, Austria: IAEA; 1996.
[97] Uchiyama Y, Yamamoto H. Greenhouse effect analysis of power generation plants. Tokyo, Japan: Central Research Institute of the Electricity Producing Industry; 1991.
[98] Uchiyama Y, Yamamoto H. Greenhouse effect analysis of power generation plants. Tokyo, Japan: Central Research Institute of the Electricity Producing Industry; 1992.
[99] Voorspools KR, Brouwers EA, D'Haeseleer WD. Energy content and indirect greenhouse gas emissions embedded in 'emission-free' power plants: results for the low countries. Appl Energy 2000;67:307–30.
[100] AEA. Environmental product declaration of electricity from Torness Nuclear Power Station. Technical report. AEA Technology; 2005.
[101] AEA. Carbon footprint of the nuclear fuel cycle – Briefing note. AEA Technology; 2006.
[102] Dones R, Bauer C, Bolliger R, Burger B, Heck T, Röder A, et al. Life cycle inventories of energy systems: results for current systems in Switzerland and other UCTE countries. Dübendorf, Switzerland: PSIand ESU-services; 2004.
[103] Fthenakis VM, Kim HC. Greenhouse-gas emissions from solar electric and nuclear power: a life-cycle study. Energy Policy 2007;35:2549–57.
[104] Hondo H, Uchiyama Y, Moriizumi Y. Evaluation of power generation technologies based on life cycle CO_2 emissions – reestimation using the latest data and effects of the difference of conditions. Tokyo, Japan: Central Research Institute of the Electricity Producing Industry; 2000.
[105] Lewin B. CO_2-emission of power plants before and after inventory energy chain. VDI Berichte 1993;1093:115–30.
[106] Vate JFvd. Full-energy-chain greenhouse-gas emissions: a comparison between nuclear power, hydropower, solar power and wind power. Int J Risk Assess Manage 2003;3:59–74.
[107] Yasukawa S, Tadokoro Y, Kajiyama T. Life cycle CO_2 emission from nuclear power reactor and fuel cycle system. Expert workshop on life-cycle analysis of energy systems methods and experience. Paris, France: Organisation for Economic Co-operation and Development, International Energy Agency; 1992. p. 151–60.
[108] Gagnon L, van de Vate JF. Greenhouse gas emissions from hydropower: the state of research in 1996. Energy Policy 1997;25:7–13.
[109] Tokimatsu K, Hondoa H, Ogawa Y, Okanob K, Yamaji K, Katsurai M. Evaluation of CO_2 emissions in the life cycle of tokamak fusion power reactors. Nucl Fusion 2000;40:653.
[110] Varun Bhat I, Prakash R. Life cycle analysis of run-of river small hydro power plants in India. Open Renew Energy J 2008;1:11–6.
[111] Varun Prakash R, Bhat IK. Life cycle energy and GHG analysis of hydroelectric power development in India. Int J Green Energy 2010;7:361–75.
[112] Vatterfall. Vattenfall AB generation Nordic certified environmental product declaration EPD of electricity from Vattenfall's nordic hydropower. Vattenfall AB Generation Nordic 2008; 2008.
[113] Odeh NA, Cockerill TT. Life cycle analysis of UK coal fired power plants. Energy Convers Manage 2008;49:212–20.
[114] Torcellini P, Long N, Judkoff R. Consumptive water use for U.S. power production. Golden, U.S.: National Renew Energy Laboratory; 2003.

[115] Pfister S, Saner D, Koehler A. The environmental relevance of freshwater consumption in global power production. Int J Life Cycle Assess 2011;16: 580–91.
[116] DOE. Concentrating solar power commercial application study: reducing water consumption of concentrating solar power electricity generation. U.S. Department of Energy; 2001.
[117] Smart A, Aspinall A. Water and the electricity generation industry. Waterlines report series No. 18. Canberra, Australia: National Water Commission, Australian Government; 2009.
[118] Li J, Shi P, Gao H. China wind power outlook 2010. Global Wind Energy Council, Greenpeace, Chinese Renewable Energy Industries Association; 2010.
[119] GWEC PR. China wind energy. Global Wind Energy Council, Brussels; 2011.
[120] Liu L-q, Wang Z-x, Zhang H-q, Xue Y-c. Solar energy development in China – a review. Renew Sustain Energy Rev 2010;14:301–11.
[121] Haszeldine RS. Carbon capture and storage: how green can black be? Science 2009;325:1647–52.
[122] Oh TH. Carbon capture and storage potential in coal-fired plant in Malaysia – a review. Renew Sustain Energy Rev 2010;14:2697–709.
[123] Wu J, Huang J, Han X, Gao X, He F, Jiang M, et al. The Three Gorges Dam: an ecological perspective. Front Ecol Environ 2004;2:241–8.
[124] Liu J, Chen F, Cui Q, Jiang Y. Ecological effect caused by hydraulic engineering construction. Front Earth Sci 2011;5:170–7.
[125] Jackson S, Sleigh A. Resettlement for China's Three Gorges Dam: socio-economic impact and institutional tensions. Commun Post-Commun Stud 2000;33:223–41.
[126] Fulford DJ, Mosley P, Gill A. Recommendations on the use of micro-hydro power in rural development. J Int Dev 2000;12:975–83.
[127] Khennas S, Barnett A. Best practices for sustainable development of micro-hydro in developing countries. IBRD, World Bank, Washington DC; 2000.
[128] Abbasi T, Abbasi SA. Small hydro and the environmental implications of its extensive utilization. Renew Sustain Energy Rev 2011;15:2134–43.
[129] Fyfe WS. Nuclear waste isolation: an urgent international responsibility. Eng Geol 1999;52:159–61.
[130] Zhou S, Zhang X. Nuclear energy development in China: a study of opportunities and challenges. Energy 2010;35:4282–8.